



UNIVERSITI PUTRA MALAYSIA

**SIMULATION ON THE PERFORMANCE OF A STIRLING COOLER
FOR USE IN SOLAR POWERED REFRIGERATOR**

KHALID OSMAN DAFFALLAH AHMED.

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By

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**Thesis Submitted to the School of Graduate Studies, Universiti Putra
Malaysia, in Fulfilment of the Requirements for the
Degree of Doctor of Philosophy**

July 2004



*To my parents, my wife, my daughter
and to all my brothers and sisters*

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in
fulfilment of the requirement for the degree of Doctor of Philosophy

**SIMULATION ON THE PERFORMANCE OF A STIRLING COOLER
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July 2004

Chairman: Professor Mohd Yusof Sulaiman, Ph.D.

Faculty: Science and Environmental Studies

Solar electricity produced by photovoltaic (PV) solar cells is one of the promising sources of power for solar refrigerator. Presently, solar PV is used to power conventional vapor compression or Rankine refrigerators. In this work, three photovoltaic freezers with different capacities and volumes of 100, 230 and 330 liters have been designed and tested. The freezers used the conventional vapor compression Rankine cycle. For the 100-liter freezer a minimum cabinet temperature of -20.1°C was obtained. The maximum and minimum cooling capacity were semi-empirically computed to be 304W and 85.8W and the corresponding power consumptions were 139W and 70.1W respectively. Coefficient of performance was calculated to be 2.19 and 1.22 respectively at the maximum and minimum temperatures. For the 230-liter freezer, a temperature of -15.2°C was achieved. The cooling capacity, power consumption, coefficients of performance were obtained semi-empirically. Similar experimental analysis was done on the 330-liter freezer to achieve a temperature of -5°C . All these freezers were tested for condenser temperature of 54°C and ambient temperature of 38°C .

Limitations of the vapor compression refrigerator were highlighted; these include insufficient power from the 75W solar panel to run the refrigerator's compressor and therefore a backup battery is always required. But, battery is expensive and has a limited charge /discharge cycles.

To allow for the use of photovoltaic module to power bigger size refrigerator, a new age of refrigeration technology such as a free piston Stirling cooler is used to replace the vapor compression refrigerator. The free piston Stirling cooler uses small amount of power effectively besides elimination of battery since free piston Stirling cooler can use phase change material to store cooling when there is insufficient power (low solar insolation and night time operation).

The general principle in which a Stirling machine self-limits its operation was presented. The proposed design of the Stirling cooler was described and the performances of the cooler were simulated using the MATLAB computer software. Three types of analyses were carried out i.e. ideal adiabatic, Schmidt and non-ideal adiabatic.

Results from the ideal adiabatic analysis showed that the total power output was 101.2W. Coefficient of performance of 3.6 was obtained, which was found to be about 21.5% of the Carnot COP. The COP was calculated for cold space temperature of -10°C and warm space temperature of 27°C . The heat absorbed by the acceptor was found to be 44.28W while the heat released by the rejector was computed to be 56.51W.

For isothermal conditions of the working space and heat exchangers, Schmidt analysis was carried out for cold space temperature of -10°C and warm space temperature of 23°C . From the MATLAB results, work done on the expansion and by the compression spaces were found to be 8.813×10^{-1} and $-9.283 \times 10^{-1} \text{J}$ respectively. Total work done was calculated to be $1.145 \times 10^{-1} \text{J}$.

The effects of the non-ideal heat exchangers and the difference in the working gas and wall temperatures were determined through a non-ideal adiabatic analysis. The gas temperature was obtained through iteration until convergence was achieved. Coefficient of performance of 3.8 was obtained for ideal regenerator and then reduced to 2.4 for a non-ideal regenerator when pumping loss was taken into account for the same temperatures of the working spaces.

Performance of operation, in terms of power consumption and cooling capacity, of the vapor compression refrigerator and Stirling type refrigerator was carried out. The comparison was based on the experimental data obtained for the vapor compression refrigerator and output data derived from MATLAB analysis for the Stirling refrigerator. The power consumption of the Stirling refrigerator was calculated to be 20W while that of the vapor compression was computed to be 139W.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**SIMULASI KE ATAS PRESTASI PENDINGIN STIRLING UNTUK
DIGUNAKAN DALAM PETI SEJUK BERKUASA SURIA**

Oleh

KHALID OSMAN DAFFALLAH AHMED

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Elektrik suria yang di hasilkan dari sel suria fotovolta merupakan salah satu punca kuasa berpotensi bagi peti sejuk suria. Pada masa ini, fotovolta suria digunakan sebagai punca kuasa peti sejuk lazim jenis mampatan wap atau Rankine. Dalam kajian ini, tiga jenis penyejuk beku fotovolta dengan keupayaan yang berlainan dan yang mempunyai isipadu 100, 230 dan 330 liter telah direkabentuk dan diuji. Penyejuk beku lazim ini menggunakan kitar mampatan wap Rankine. Untuk penyejuk beku yang mempunyai isipadu 100 liter, suhu peti pada -20.1°C telah diperolehi. Keupayaan penyejukan maksimum dan minimum masing-masing bersamaan 304W dan 85.8W telah dikira secara semiempirik bersama-sama kuantiti penggunaan kuasa yang berpadanan bersamaan 139W dan 70.1W. Nilai pekali prestasi bersamaan 2.19 dan 1.22 telah dihitung pada suhu maksimum dan minimum. Untuk penyejuk beku yang mempunyai isipadu 230 liter, suhu pada -15.2°C telah diperolehi. Kuantiti seperti keupayaan penyejukan, penggunaan kuasa, pekali prestasi telah diperolehi secara semiempirik. Analisis eksperimen yang sama telah dilakukan ke atas penyejuk beku yang mempunyai isipadu 330

liter dan telah menghasilkan suhu pada -5°C . Semua penyejuk beku ini telah diuji untuk suhu kondenser pada 54°C dan suhu ambien pada 38°C .

Kelemahan peti sejuk jenis mampatan wap telah dinyatakan dan ini termasuk ketidakupayaan kuasa panel suria 75W untuk mengoperasi alat pemampat peti sejuk sehingga memerlukan penggunaan bateri penyokong pada sepanjang masa. Tetapi, penggunaan bateri adalah mahal malah bateri mempunyai kitar cas/nyahcas yang terhad.

Untuk membolehkan penggunaan modul fotovolta menguasai peti sejuk yang lebih besar, teknologi peti sejuk era baru seperti pendingin piston bebas Stirling lebih sesuai digunakan untuk menggantikan peti sejuk jenis mampatan wap. Pendingin piston bebas Stirling berupaya menggunakan dengan berkesan kuasa yang lebih kecil untuk membolehkan bateri diganti dengan bahan bolehubah fasa. Bahan seperti ini boleh digunakan untuk menyimpan tenaga penyejuk apabila kuasa elektrik berkurangan (dalam keadaan penyinaran suria yang rendah dan ketika malam hari).

Prinsip umum yang membolehkan mesin Stirling menghadkan operasinya juga telah diberikan. Cadangan rekabentuk pendingin Stirling telah diterangkan dan prestasi pendingin ini telah disimulasi dengan menggunakan perisian komputer MATLAB. Tiga jenis analisis telah dijalankan iaitu, analisis adiabatik unggul, analisis Schmidt dan analisis adiabatik tak unggul.

Hasil dari analisis adiabatik unggul memberikan jumlah kuasa bersamaan 101.2W. Pekali prestasi bersamaan 3.6 telah diperolehi, iaitu 21.5% daripada pekali prestasi Carnot. Pekali prestasi ini telah dikira untuk suhu ruang dingin pada -10°C dan suhu ruang hangat pada 27°C . Haba yang diserap oleh alat penyerap telah dikira dan didapati bersamaan 44.28W sementara haba yang dibebaskan oleh alat pengasing haba bersamaan 56.51W.

Untuk ruang kerja dan penukar haba jenis isoterma, analisis Schmidt telah dijalankan untuk suhu ruang dingin pada -10°C dan suhu ruang hangat pada 23°C . Hasil dari pengiraan MATLAB, kerja yang dilakukan oleh ruang pengembangan adalah bersamaan $8.813 \times 10^{-1}\text{J}$ dan kerja yang dilakukan ke atas ruang pemampatan bersamaan $-9.283 \times 10^{-1}\text{J}$. Jumlah kerja yang dilakukan telah juga dikira dan didapati bersamaan $1.145 \times 10^{-1}\text{J}$.

Analisis telah juga dilakukan dengan mengambilkira kesan dari penggunaan alat penukar haba yang tak unggul dan perbezaan suhu dinding gas dari ruang kerja. Suhu gas telah diperolehi dengan cara pelelaran sehingga hasil penumpuan diperolehi. Pekali prestasi bersamaan 3.8 telah diperolehi untuk alat penjana semula yang unggul dan nilai ini telah berkurangan kepada 2.4 apabila alat penjana semula tak unggul digunakan. Dalam alat penjana semula tak unggul berlaku kehilangan tekanan pada suhu ruang kerja yang sama.

Analisis prestasi operasi yang berkaitan dengan penggunaan kuasa dan keupayaan penyejuk bagi peti sejuk jenis mampatan wap dan Stirling telah dijalankan.

Perbandingan telah dibuat berasaskan kepada data eksperimen bagi peti sejuk jenis mampatan wap dan data yang diperolehi dari analisis MATLAB bagi peti sejuk jenis Stirling. Penggunaan kuasa bagi peti sejuk jenis Stirling telah dikira dan didapati bersamaan 20W sementara bagi peti sejuk jenis mampatan wap bersamaan 139W.

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I certify that an Examination Committee met on 22nd of July 2004 to conduct the final examination of Khalid Osman Daffallah Ahmed on his Doctor of Philosophy thesis entitled "Simulation on the Performance of a Stirling Cooler for Use in Solar Powered Refrigerator" in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

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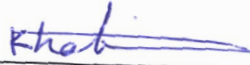
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DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.



KHALID OSMAN DAFFALLAH

Date: 20.8.2004

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LIST OF SYMBOLS AND ABBREVIATIONS

PV	Photovoltaic
BLDCM	Brushless DC Motor
P-h	Pressure-enthalpy
COP, ε	Coefficient Of Performance
Q_E	Heat absorbed by the evaporator
Q_C	Heat rejected by the condenser
W_C	Work done to drive the compressor
T_E	Temperature of the evaporator
T_{ER}	Temperature of the refrigerant in the evaporator
T_C	Temperature of the condenser
T_{CR}	Temperature of the refrigerant in the condenser
ε_C	Cartnot COP
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
T_e	Expansion temperature
T_c	Compression temperature
pV	Pressure-volume
TS	Temperature-entropy
cs	Compression space
es	expansion space
PV-TE	Photovoltaic Thermoelectric